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RAIL ROAD WHEEL: DESIGN, PERFORMANCE AND MANUFACTURING ASPECTS

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ABSTRACT

Railroad wheels do the toughest job. Design of wheel web and material used are the most important. Online performance specifies the material properties required. Wheel manufacturing process using upward pressure poured casting and the quality assurance system, which makes it reliable has been explained. Initially these wheels were used for freight stock only and subsequently based on their reliable performance, they are also used on locomotives and coaching stock.

KEYWORDS: Railroad Wheels, Pressure Poured Casting, Thermal Load, Fatigue Strength, Web-Offset & Rail-Wheel Interaction

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Original Article

INTRODUCTION

The wheel is probably (1) the most important mechanical invention of all time and were used in chariot for transportation in 3200 BC.

Wheels have to do the toughest job in a loaded rail road car. That is it supports the weight of a heavily loaded car, thermal load of braking and impacts of railway track irregularities.

As shown in figure 1(a), a typical rail road wheel consists of three parts, a hub, a rim and a web that unites the two parts. The outer circumferential surface of the rim, which contacts the rail, is tread, and the projected part is flange. Earlier tyred wheels were used and now they are solid or mono-block wheels. Wise (2) has given a brief history of the evolution of rail road wheel sets.

The satisfactory performance of a railroad wheel depends (3,4) on its ability to withstand repeated stresses imposed on it by normal loads and braking conditions, and also the occasional high stresses that develop under abnormal operating conditions.

The rim width and thickness, hub diameter and length and position of rim relative to the hub are wheel parameters dictated by service requirements and leave little room for manoeuvre. The web shape, however can take on many forms.

WEB

Kinds of Mechanical Loads

There are two kinds of mechanical load exerted onto a wheel: vertical load and lateral load. As shown in

Figure 1(a), vertical load V is one produced by supporting the car weight in the vertical direction. The horizontal or lateral load L is acting onto the flange fillet of the outer wheel from the outer side of the curved track to the inner side. It also acts from the back side of inner wheel's flange while passing over guard rail which is less frequent in comparison to that from front side.

Types of Web Configuration

Typical web configurations of the wheels (5) are shown in figure 1.

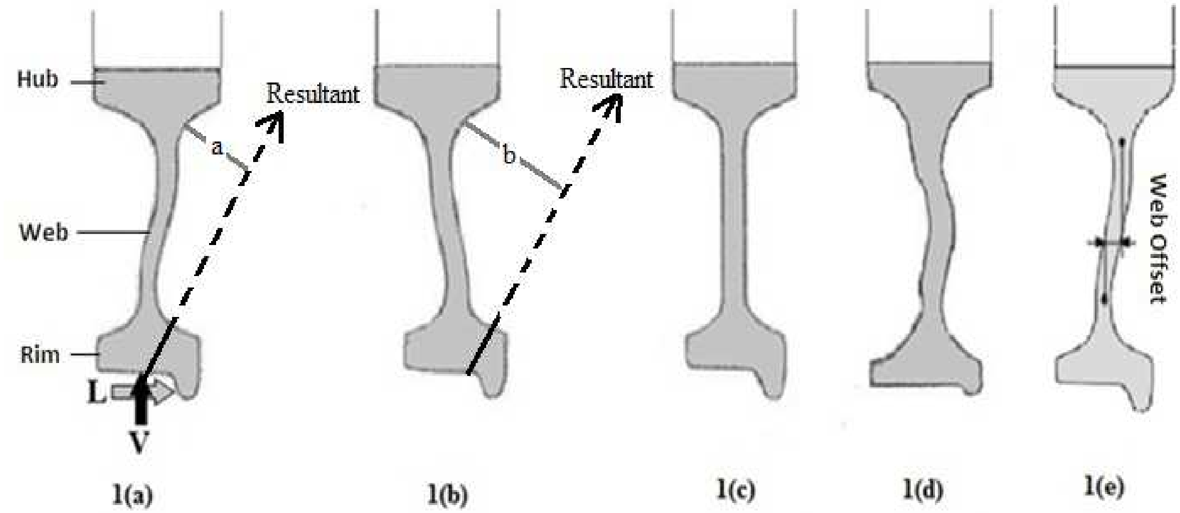

Figure 1(a): Inside Web, (b) Outside Web, (c) Straight Web, (d) Double Curved Web, (e) Off-set Web

A wheel is subjected to lateral load L during curve negotiation, hunting and/ or nosing on straight track also.

These loads are also important for the stability analysis (6) (such as derailment criteria) and riding comfort.

The resultant of the two forces acts in an upward direction at the contact point with the rail, inclining toward the inside of the wheel set. The maximum stress in the web is generated at the hub/ web transition. Since the arm length of Type A is shorter than that of Type B, the bending moment 'a' of Type A, is less than 'b' that of Type B even when the loading conditions are the same. In other words, the web configuration of Type A is superior with respect to strength (7).

Configuration of Type B is designed for creating a space inside of a driven wheel set and that of Type C is designed generally for a wheel equipped with disc brakes on both sides.

Thermal Load Due to Tread Braking

In addition to its primary task of carrying load, in most cases the wheel also has to act as a brake drum. The frictional heat depends on the type of braking.

Temperatures can reach the 600-700^0 C range in drag braking and during stop braking temperature range is 100-300^0 C(5). Therefore drag braking produces higher web stresses.

The frictional heat transferred to the tread tends to expand the rim radially. This `expansion is restrained by the web which is at a lower temperature; consequently stresses are produced in the web. These stresses are much higher than those induced by mechanical loading. The magnitude of the stresses and the position of maximum stress depend on the

geometrical shape of the web.

Fatigue Strength of Web

Since cyclic mechanical stresses are exerted on the web, the web material must have sufficient fatigue strength to withstand the stress cycle.

Hirakawa et al. (7) conducted fatigue test with full size wheels. As shown in Figure 2, stress amplitude initially reduces with increasing cycles of application and then stabilises at 240 MPa at cycles above 10^6. In other words the fatigue strength is approximately 240 MPa. Normally an allowable stress of 157 MPa is considered for web design, which has a factor of safety of 1.5.

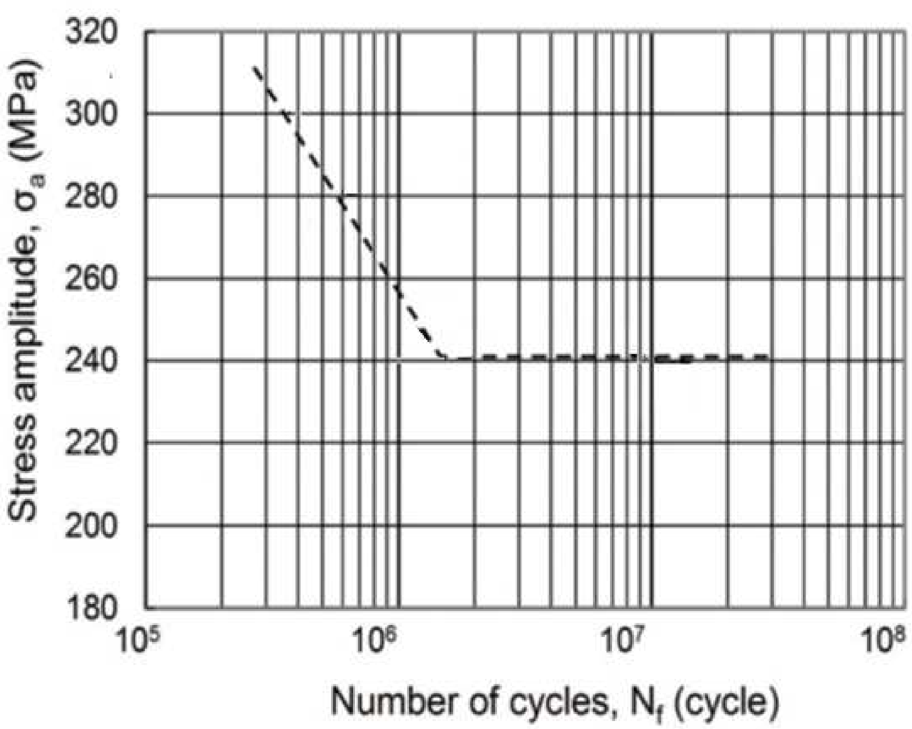

Figure 2: Fatigue Test Results of the Domestic Wheels

Reversal Change of the Residual Stress

Tread braking results in rise of tread temperature due to friction. Stop braking usually does not influence the performance of the wheel. Whereas, drag braking when running a long downhill or a stuck brake shoe due to malfunction of a braking system heats the whole rim section to a high temperature. Because of the thermal expansion of the rim, the rim pulls the web outward, and then tensile radial stress is generated in the web area.

When this thermal radial stress exceeds the yield stress of the web material, outward plastic deformation of the web takes place. After the brake shoe is released and the wheel is cooled, the rim tends to shrink; however, the expanded web disturbs the rim to shrink. As a result, the web pushes the rim outwardly, and then causes the tensile stress in the rim. The compressive residual stress is originally given by heat treatment, during the wheel manufacture. However, this initial residual stress changes from the compression side to the tension side due to thermal input by braking. In general mean tensile stresses are detrimental and compressive mean stresses are beneficial to fatigue life of wheel (8). This is the "reversal change in the rim residual stress." Once this happens, small thermal cracks on the tread surface start to propagate

and result in a brittle fracture of a wheel in the worst case. Accordingly, stress in this situation is very dangerous.

However, according to studies conducted, it was found that this change in residual stress can be controlled by improving the web configuration (9). The key parameter is the web offset, as shown in figure 1(e).

As is clear from the graph in the figure 3, the thermal stress reduces from 600 to 200 MPa when the web offset is increased to 80 mm. This means that the web offset can reduce the plastic deformation of the web because of yielding. Therefore, the shrinking of the rim is not disturbed by the web when cooling, and consequently, the reversal change in the residual stress in the rim does not occur. A High Toughness (HT) wheel was developed on this concept by the then Sumitomo Metal Industries, Ltd.

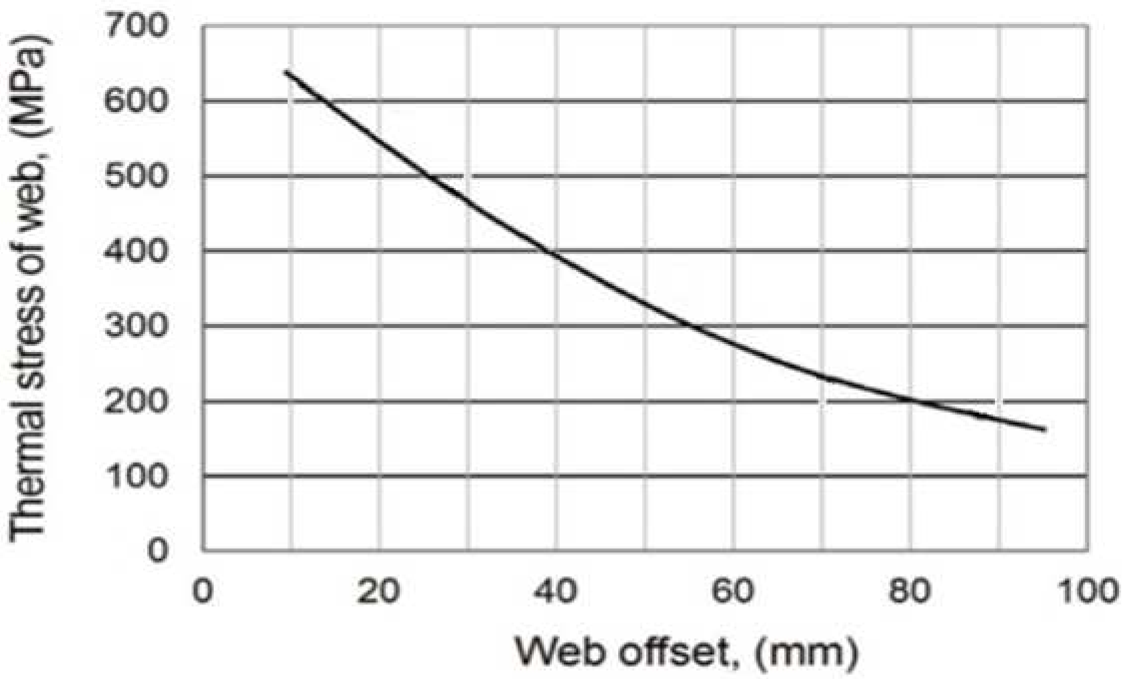

Figure 3: Thermal Stress of Web Depending on Web Offset

RIM - WHEEL MATERIAL

A rim has to be resistant towards wear, thermal cracks, fracture and rolling contact fatigue.

Earlier wheel material was low carbon steel (carbon content of around 0.5%). It was estimated that increase in carbon content would be effective to give the wheel a longer life; however, it might shorten the rail life.

Rail Wear and Wheel Hardness

Dr. Saito et al. [7] conducted trials with 1/3 scale model wheel-carriage in the premises of the Sumitomo Metal Industries, they measured the amounts of wear of rails and wheels for various combinations of materials.

After around seven years of investigation, they concluded that the increase in the carbon content of a wheel reduces not only the wheel wear but also the rail wear.

Comparative investigation of wheel materials and of their influence on rail wear was also done by Deutsche Bahn (7). These trials were conducted on full size wheel-rail testing rig as well as on actual trains. On the basis of these trial

results, it was concluded that the rail wear is not effected by the higher carbon content of wheel material.

Comparison of Forged and Cast Wheel

Wheel/ Rail wear testing was conducted on test stand (10), to compare Forged/ rolled wheels and pressure poured cast wheels using AAR class B &AAR Class C chemistry. The results indicated that the class C pressure poured cast wheel has no adverse effect on rail wear. Actually, both the wheel wear and rail wear are significantly less for class C wheel.

Rail- Wheel Interaction

Mutton and Epp (11) found that on 20 tonne axle load tests, the wear rate of standard carbon rails at high flanging stresses is higher even with softer wheel materials. According to them the increase in rail wear rate is partly due to the deterioration of wheel flange profile by both wear and plastic flow, which give rise to more severe contact conditions. Therefore higher strength materials are likely to retain profiles for longer periods. In other words rail-wheel interaction does not deteriorate due to less wear, hence better performance.

Thermal Crack Resistance and Fracture Toughness of the Rim

In case of a wheel with tread brake, even under normal braking condition, initiation of very fine thermal cracks at the tread surface layer cannot be avoided because of cyclic heating and cooling and they lead to a brittle fracture. Fracture resistance varies with type of material. Fracture toughness is an indicator of this resistance. Figure 4 shows the relationship between the fracture toughness of the rim and carbon content (7). There is a drop in fracture toughness from 90 to 50 with an increase in carbon % from 0.5 to 0.6. Subsequent increase in carbon % does not effect appreciably. In other words low carbon % has better thermal crack resistance and fracture toughness, but has less resistance against wear.

Railroad vehicle is a guided vehicle therefore rail-wheel contact geometry is important for stability and safety. Wear of geometry of rail and wheel contacting profiles effects the negotiability and hence life and performance. So low carbon percentage, which is less resistance to wear is not considered for use.

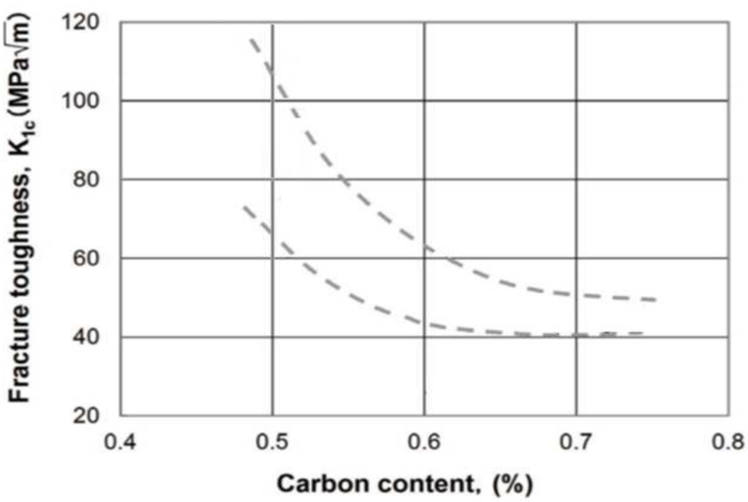

Figure 4: Fracture Toughness Depending on Carbon Content

AAR's steel grade of Class D, has higher hardness than Class C. However, its carbon content is same as that of Class C, which belongs to high carbon steel (Table 1). It covers micro-alloyed steels with superior properties.

Table 1: Steel Grades Specified by AAR

Steel Grade	Carbon Content	Hardness
Class A	0.47 – 0.57	255 - 321
Class B	0.57 - 0.67	302 - 341
Class C	0.67 – 0.77	321 - 363
Class D	0.67 – 0.77	341 - 415

MANUFACTURING OF WHEELS

The characteristics required for the passenger car and the freight car are not the same. Reliability is of first priority for passenger car wheels; whereas, for freight car wheels, the greatest interest concern is initial and maintenance cost.

In India both the freight and the passenger services are equally important. Indian Railways runs every day 7000 freight trains and 12000 passenger trains, which is one of the largest network in the world.

Indian Railways has two wheel production units, one at Bangalore and the other at Chapra.

Prior to these wheels were procured from Steel Authority of India (SAIL) and import. SAIL produces forged wheels.

Wheel manufacturing plant at Bangalore came up in 1984 (13, 14). This production unit produces cast wheels. Griffin cast wheel technology was adopted here. Same technology is being used at Chapra plant also.

Manufacturing Process

Superior quality scrap is melted in electric arc furnace, after checking chemical composition; molten metal is tapped in a ladle. Micro cleanliness and micro alloying is done in the ladle. Chemical composition is checked. As shown in figure 5, the ladle is put in John Mohr Pit where a pre-treated graphite mould is filled by upward pressure pouring (Figure 5). Then this cast wheel is subjected to sprue wash, hub cutting, heat treatment and various checks. These are given in Figure 6.

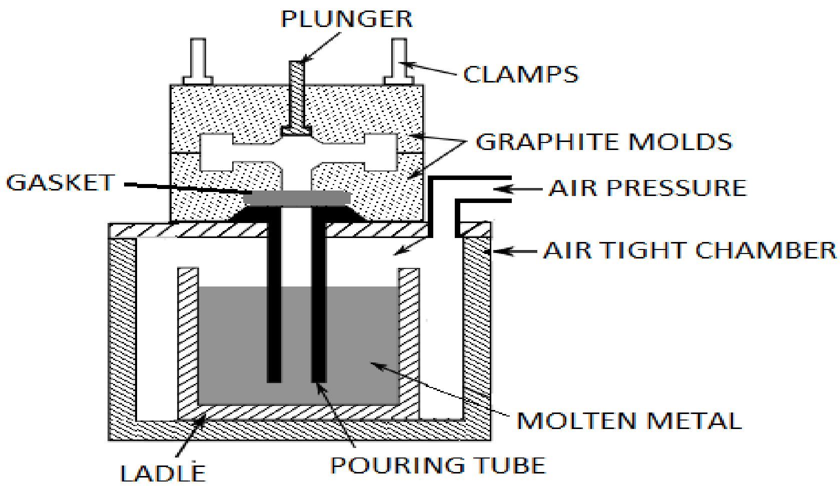

Figure 5: Pressure Poured Casting of Wheel

Following flow diagram gives the process of wheel manufacturing:

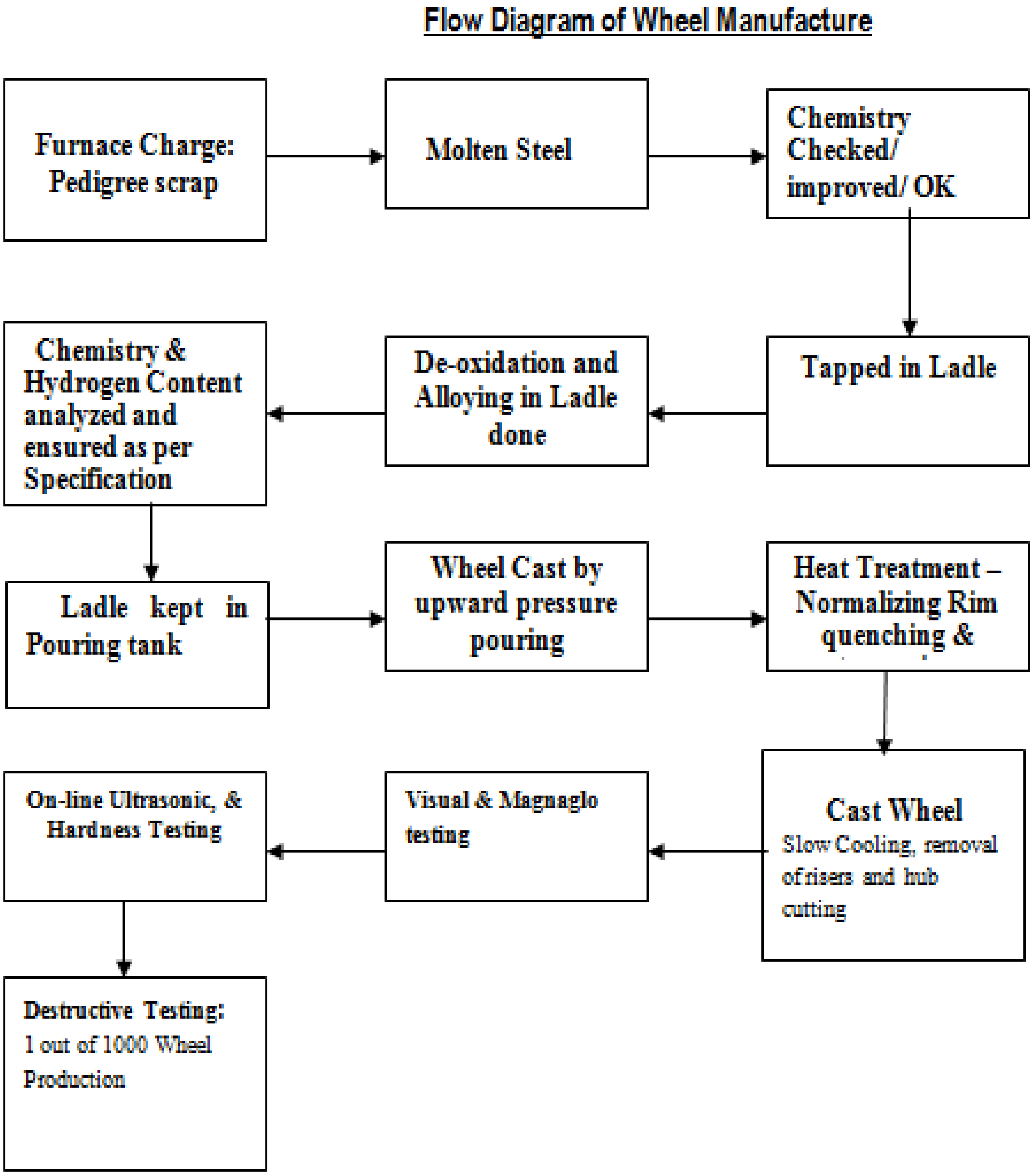

Figure 6: Manufacturing Process of Wheel

In addition to various online quality assurance checks, one wheel in a production lot of 1000 wheels is taken out for destructive testing for checks such as distribution of hardness in the cross-section (a typical pattern is shown in figure 7), fracture toughness, elongation, closure value, UTS, microstructure, grain size, yield strength, chemical composition, micro-cleanliness.

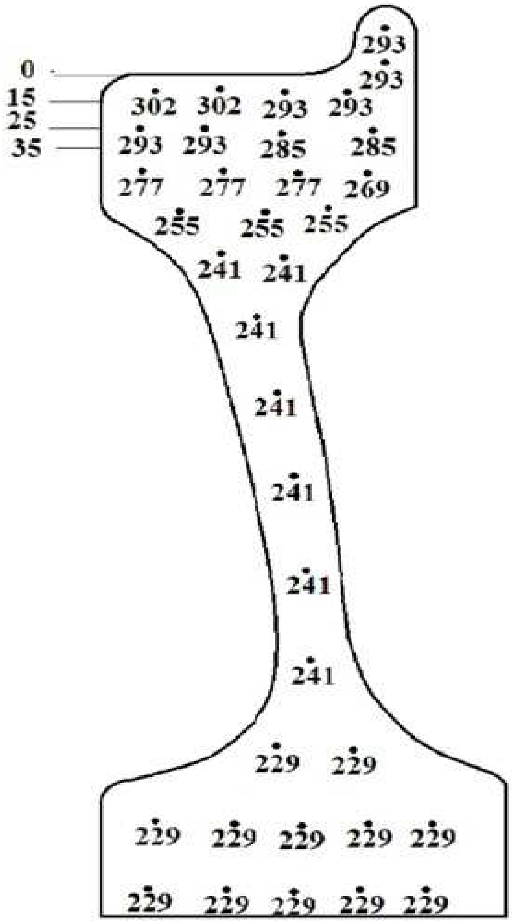

Figure 7: Hardness Distribution

Production Details of Bangalore Plant

This plant was set up as an import substitution of freight stock BOXN wheels. Subsequently this technology was adopted for locomotive wheels first and later on for coaching stock wheels. Table 2, gives production of wheels from 1990 to 2012, which has increased from 47K to 200K.

Table 2: Production over the Years

Year	1990	2000	2005	2009-10	2011-12
Wheels	47139	95591	117425	187480	201135

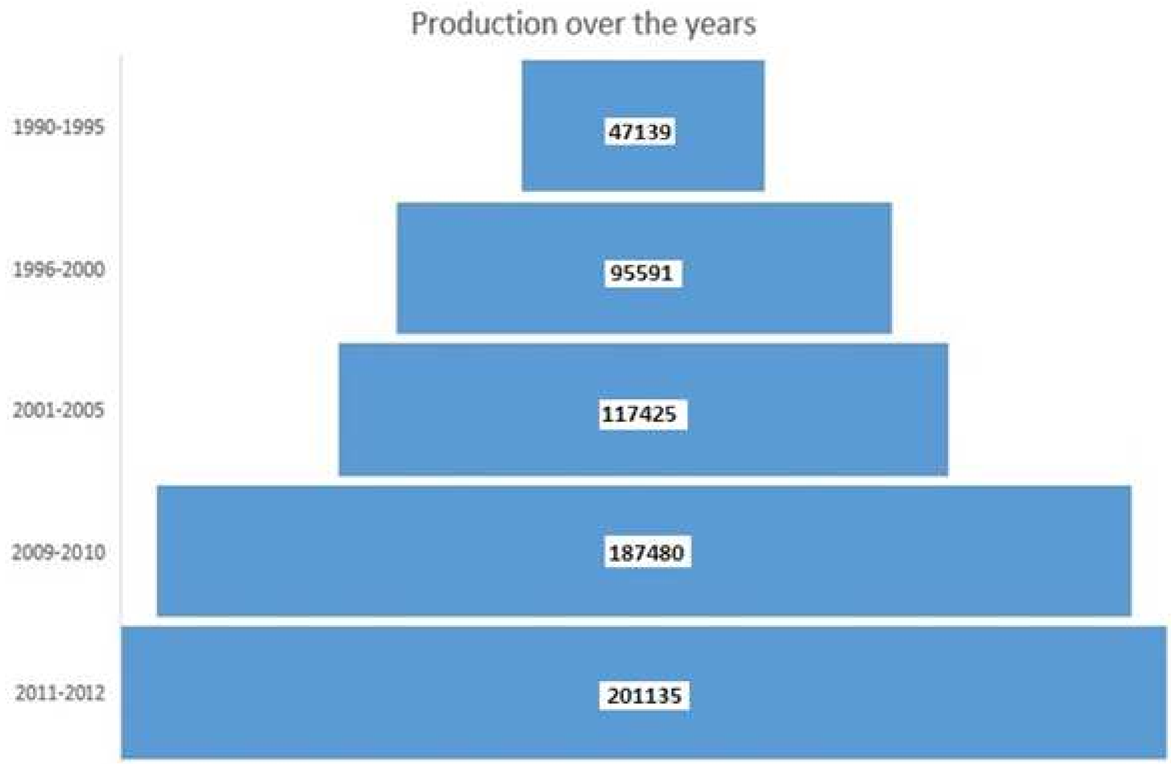

Figure 8: Production of Cast Wheels

So far no online-failure of these wheels has taken place. In other words these cast wheels are more reliable.

With this success locomotive and coaching stock wheels were also produced between 2000-2004. Initially these were having casting defects. Then casting simulation software was used to modify locations and size of risers. With these modifications casting produce were sound. There after finite element analysis using NISA software was done and these wheels were got tested at Transportation Test Centre Inc. (TTCI) USA. Indian Railways uses multiple wear wheels. TTCI found FEA analysis ok and wheels very sound for use.

CONCLUSIONS

Design of railroad wheel is limited to changes in web as other parameters are dictated by the gauge and moving dimensions of the standard adopted. Initially it was tyred wheels and now mono block. With increasing load and speed of train services, focus was on the chemistry and heat treatment. Subsequent fatigue performance in services brought fracture toughness and micro-cleanliness into focus.

Griffin Cast wheel technology is more suited for mass production. Automation and quality is built-in in the system. Griffin's cast wheel technology was adopted as a measure to cut down import on freight service wheels, which is considered inferior as compared to reliability requirements of passenger service. After use in freight service, these were found reliable and subsequently this manufacturing technology was adopted in superior services of coaching stock and locomotives.

The plant at Bangalore was set up at a cost of INR 1.45 billions in 1984, when plant capacity was 50000 wheels. Subsequently measures were taken to augment the capacity and develop wheels for locomotive and passenger services because of proven reliability of cast wheels. This plant has now a turnover of 200000 wheels, which is more than INR 10

billions annually with zero-online failure. In other words it's financially viable also.

Two important streams for manufacturing are forging and casting. Normally forging process is considered superior over casting but pressure poured precision casting offsets this belief because of effectiveness of inbuilt quality system.

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